

Volatile Analysis by Pyrolysis of Regolith (VAPoR) on the Moon using Mass Spectrometry

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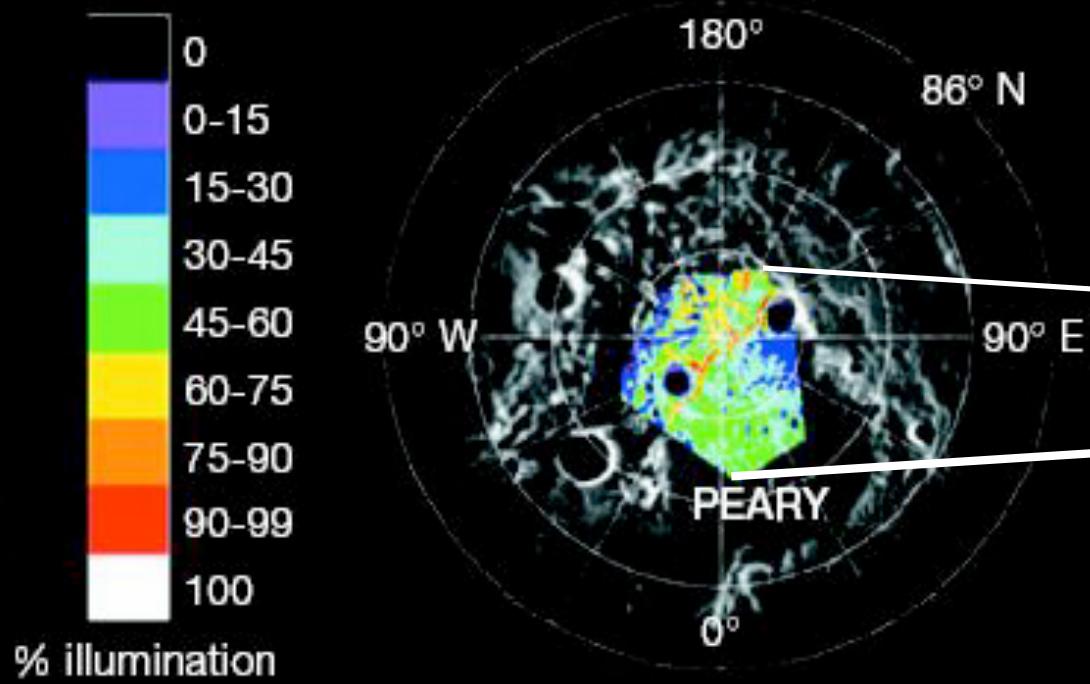
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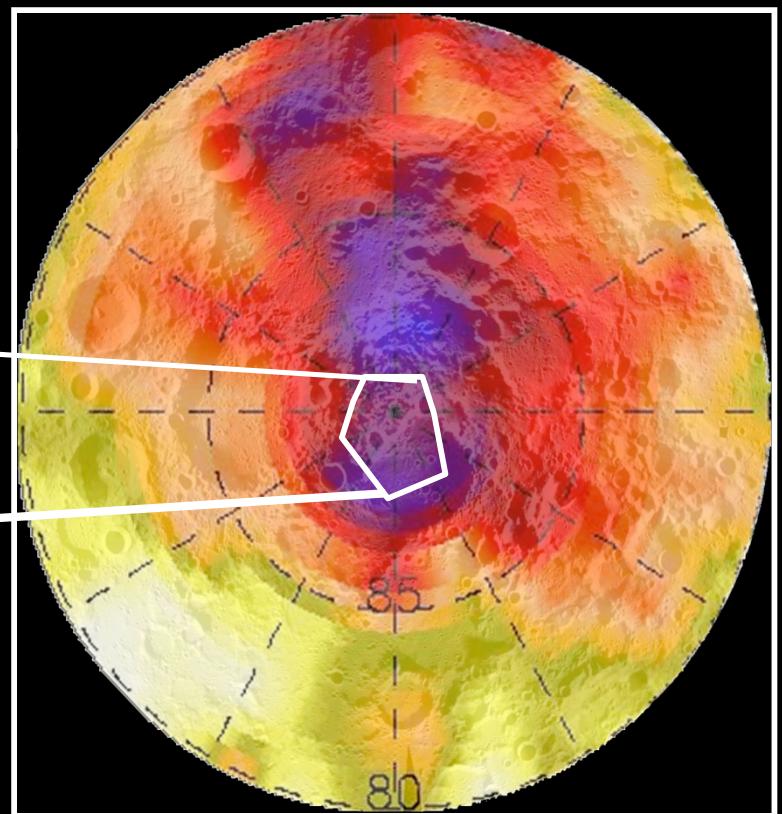
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Is there water-ice at the lunar poles?

Clementine: High circular polarization ratio (CPR) over dark areas at poles; No enhancement in sunlit areas.



Bussey et al. 2005; Fristad et al. 2004



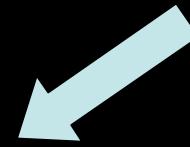
The source of enhanced hydrogen at the poles remains controversial. In situ measurements will be necessary to determine the composition, abundance, spatial distribution, and source of lunar volatiles.

Potential Sources of Lunar Volatiles

Earth
(contamination, possible
terrestrial meteorites)



Solar wind
(implanted H,C,N, He, Ne)



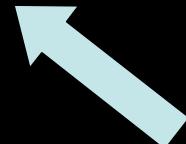
Moon
(radioactive decay,
outgassing)



Comets and Asteroids
(water-ice, organics?)

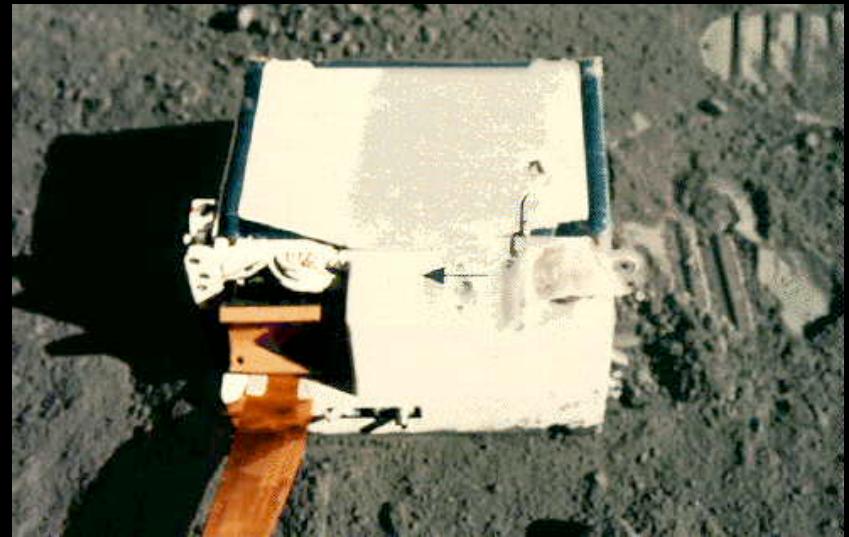


Interplanetary
dust particles



Lunar Atmospheric Composition Experiment (LACE)

- Magnetic deflection mass spectrometer (1 to 110 amu)
- Measured surface atmospheric composition during Apollo 17
- Detected H₂, He, Ne, Ar and trace levels of CH₄, NH₃, H₂O and CO₂
- Sources: chemical reactions with solar wind implanted ions, outgassing, and/or exchange with cold traps

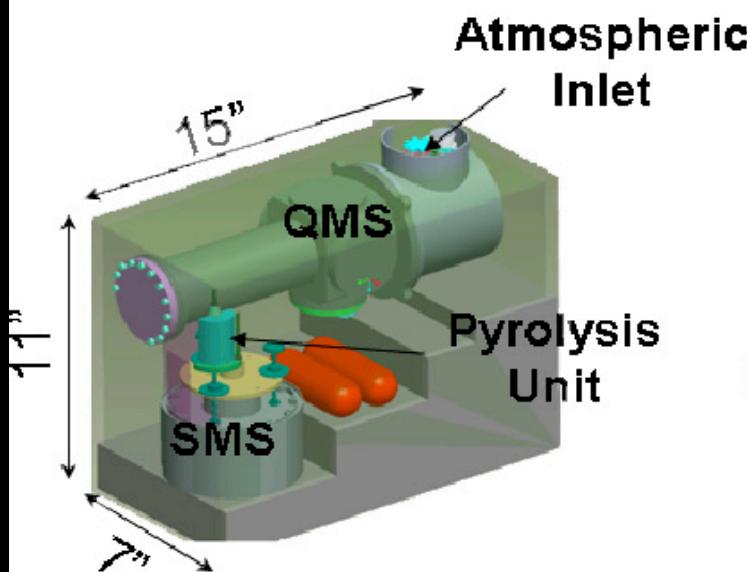


LACE PI: John Hoffman

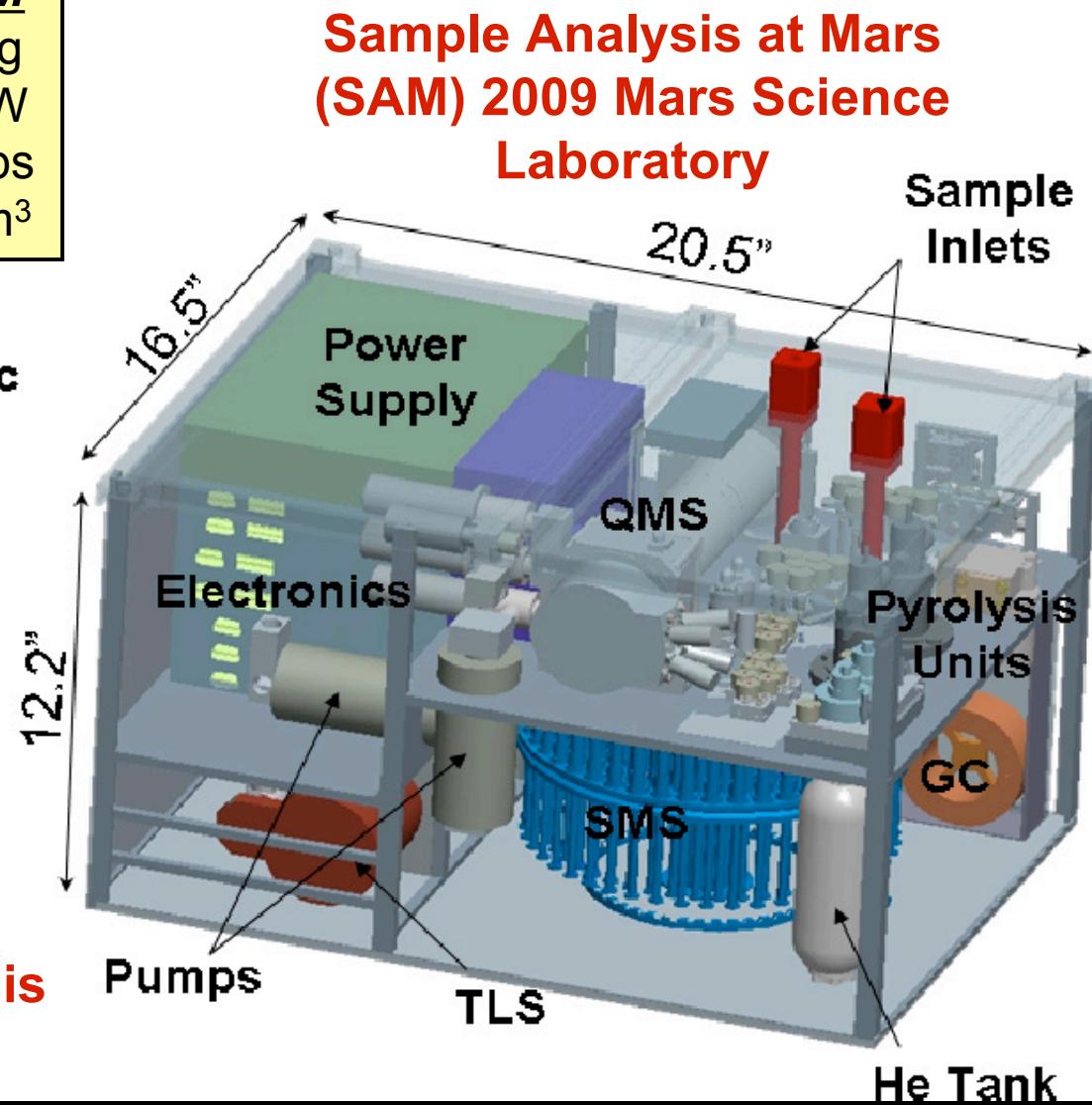
**Surface regolith samples
not analyzed by LACE**

VAPoR is a Miniature Version of SAM

	VAPoR	SAM
Mass:	7-15 kg	40 kg
Power:	25-35 W	60-80 W
Data rate:	1 kbps	<100 kpbs
Volume:	19 dm ³	68 dm ³



Volatile Analysis by Pyrolysis of Regolith (VAPoR)



Key Science Objectives

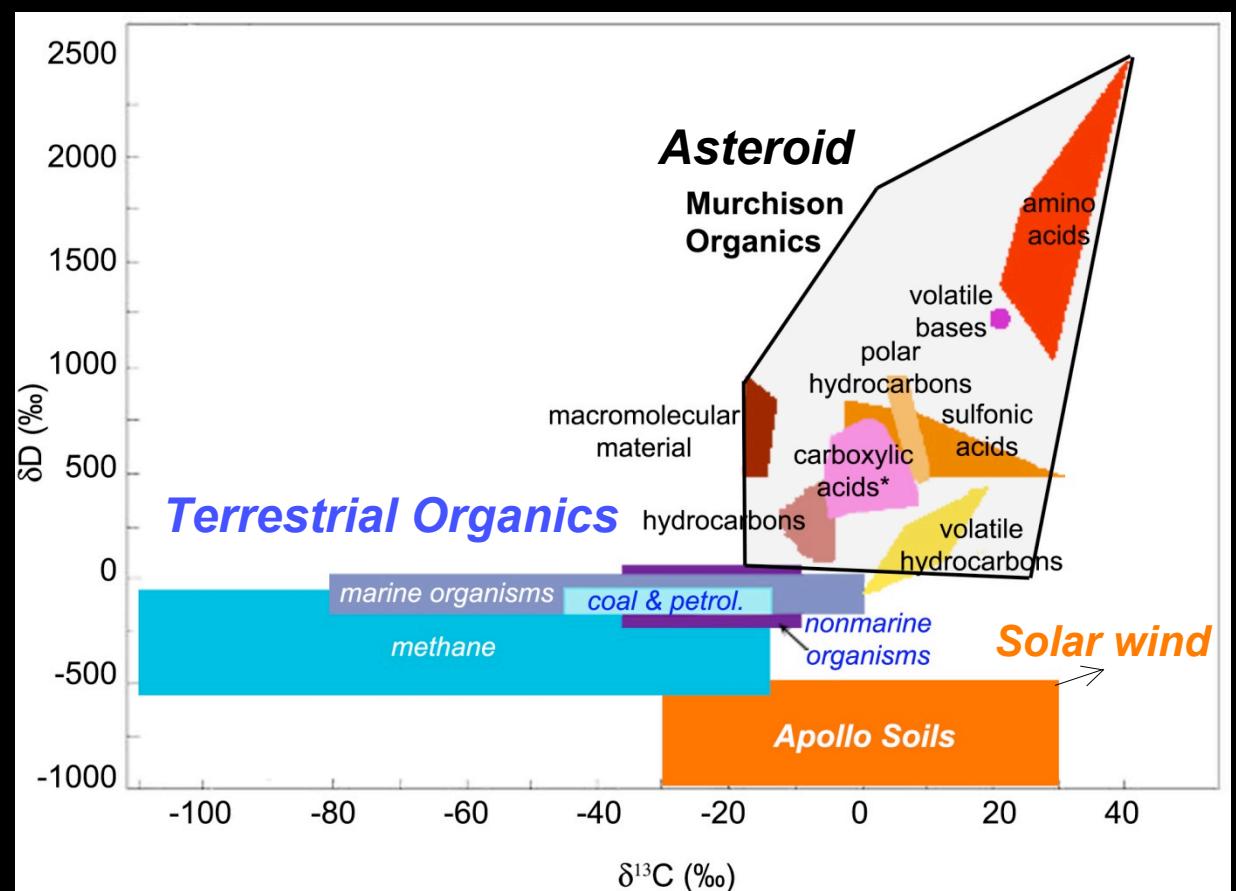
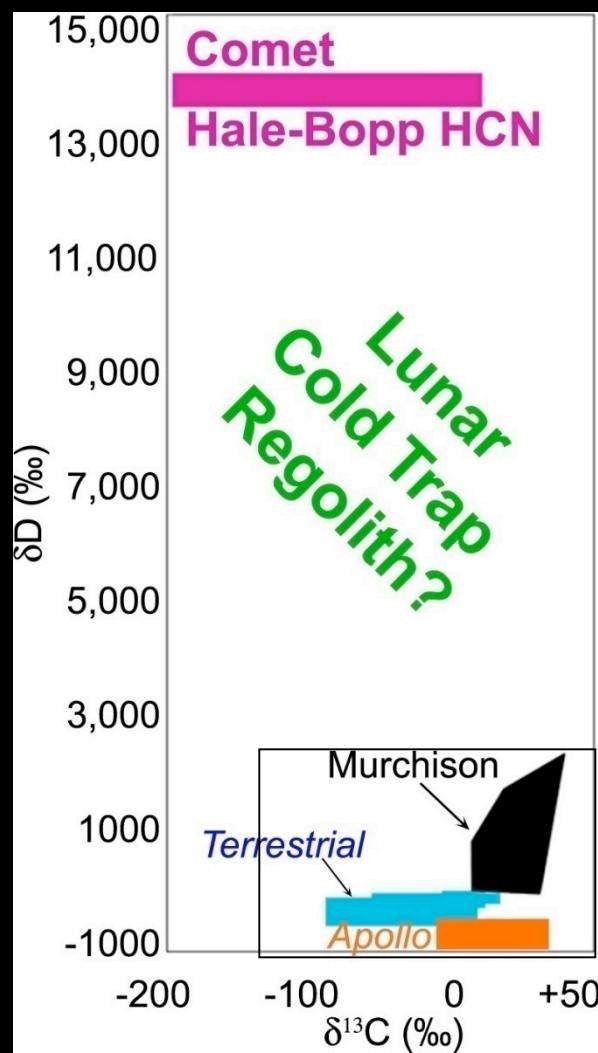
- 1) Determine the composition, abundance, spatial distribution, and source of lunar volatiles associated with polar hydrogen deposits.
- 2) Characterize the native lunar atmosphere at the poles.
- 3) Understand the processes by which terrestrial organics or volatiles are dispersed and/or destroyed on the Moon.
- 4) Evaluate the potential of the polar regolith for future in situ resource utilization (ISRU).
- 5) Identify potentially hazardous volatiles (e.g. radon)

VAPoR can address ALL of these lunar surface science measurement objectives

VAPoR Measurements of Lunar Atmosphere and Regolith

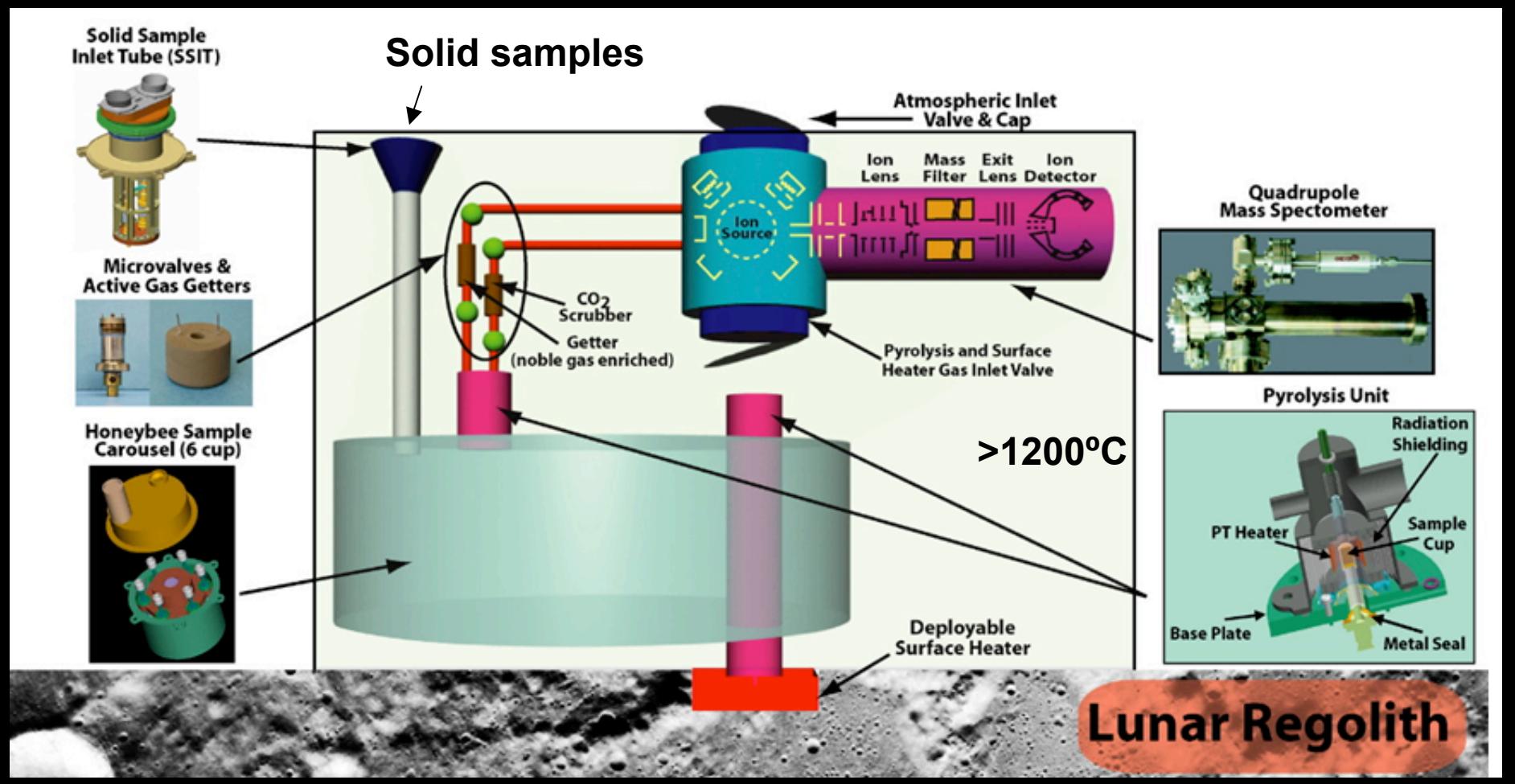
Objective	Requirements		Capability
Origin of Volatiles (Isotopes)	C,H,O,N-Volatiles	Measure D/H in water	~10‰ (per mil)
		Measure $^{13}\text{C}/^{12}\text{C}$ ratio in CO ₂ from regolith	~5‰
		Measure $^{16}\text{O}/^{18}\text{O}$ in CO ₂	5‰
		Measure $^{14}\text{N}/^{15}\text{N}$ in N ₂	5‰
	Noble Gases	Measure Ne abundance and isotopes	10‰
		Measure Ar abundance isotopes	5‰
		Measure Kr and Xe abundance and isotopes	5-20‰
Resources (ISRU)	Organics	Detect volatile hydrocarbons and measure abundance at ppb to ppm level	Mass range: 1-250 amu, LOD: sub ppm
		Measure $^{13}\text{C}/^{12}\text{C}$ ratio of CO ₂ from organics combustion	~5‰
		Measure abundance of H ₂ O, H ₂ , CO ₂ , CO/N ₂ in atmosphere and regolith	~ 1 ppm
		Measure He abundance	$^{3}\text{He}/^{4}\text{He}$ (TBD)
		Measure abundance of O ₂	>1200°C, 5% low conductance leak
		Measure reduced inorganic gases (e.g. H ₂ S)	< 20 ppb

Isotope measurements will help constrain the origin of lunar volatiles



e.g. D/H and ¹³C/¹²C ratios

VAPoR can be integrated into an autonomous suitcase-sized package

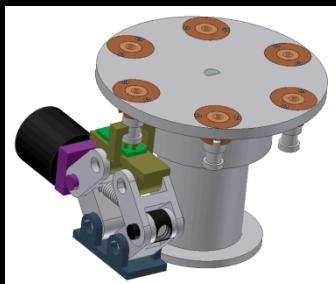


Sample Manipulation System (SMS)

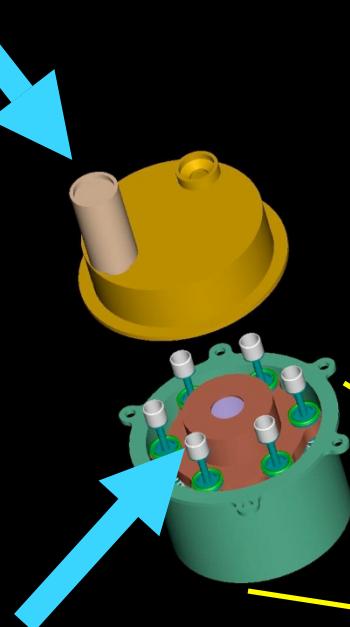
D. Roberts, E. Mumm, and S. Gorevan (Honeybee Robotics)



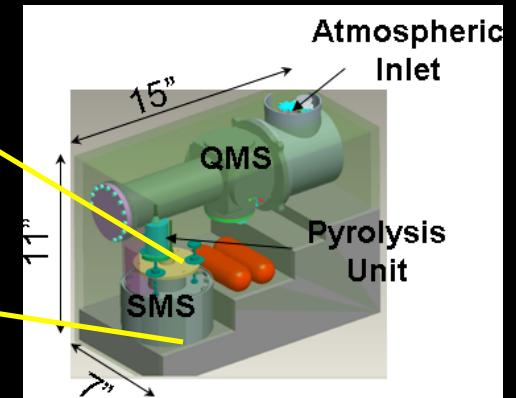
Lunar regolith core samples collected robotically or by an astronaut and delivered to inlet of 6 cup sample carousel. Solid sample inlet tube developed for SAM.



VAPoR sample heater cups sealed to mass spectrometer and heated individually to 1200°C for quantitative volatiles analysis.

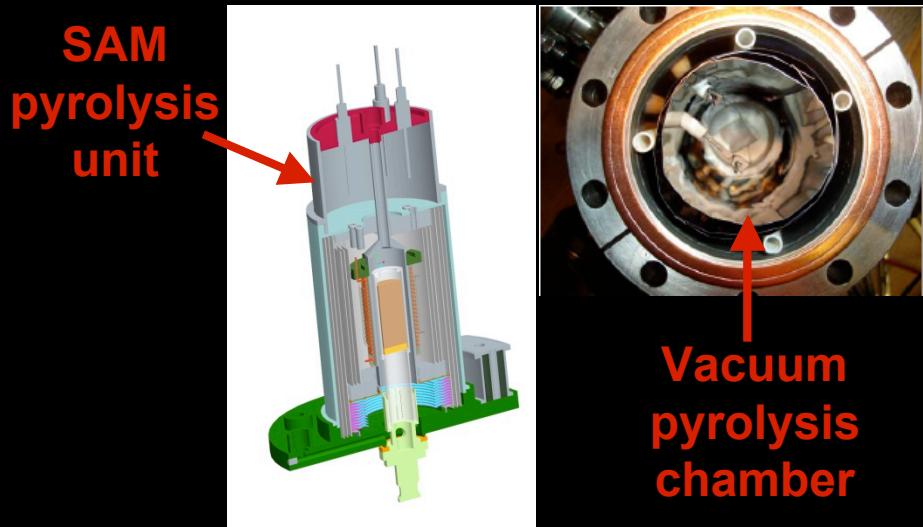
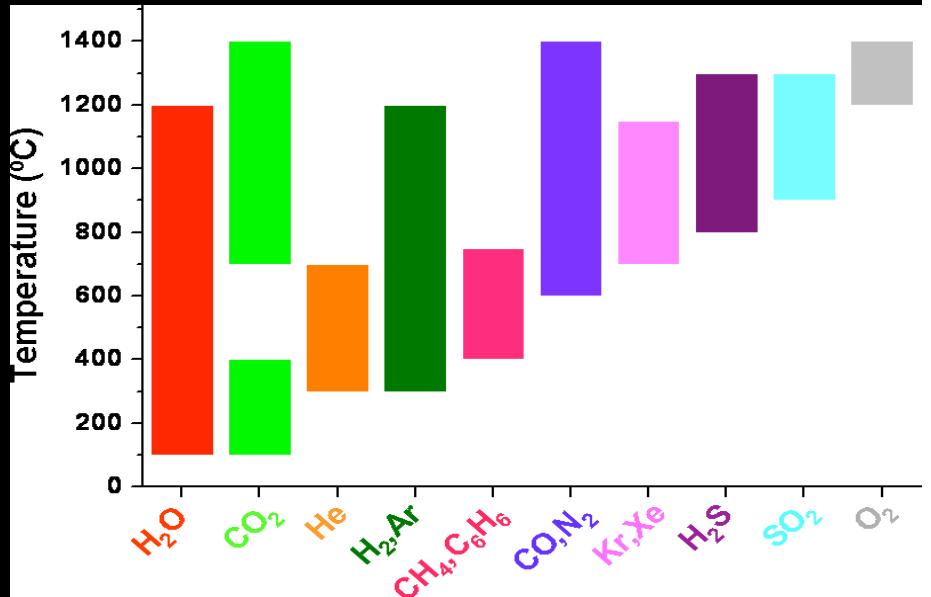


VAPoR



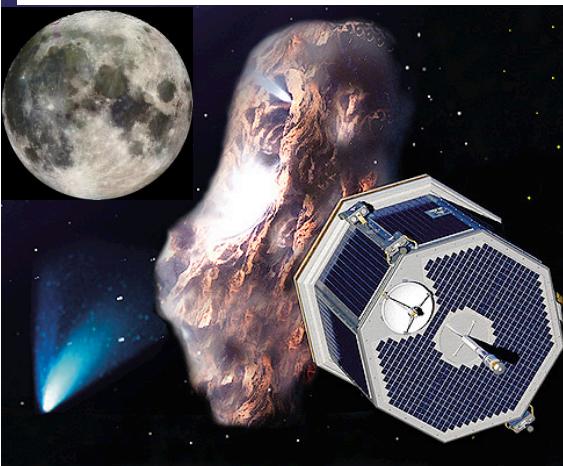
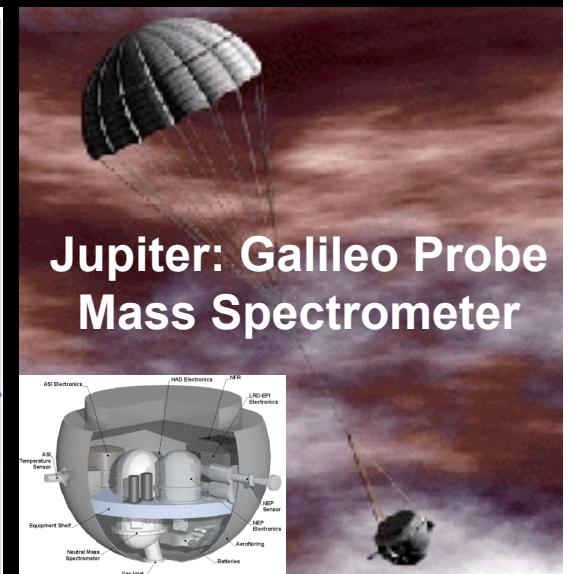
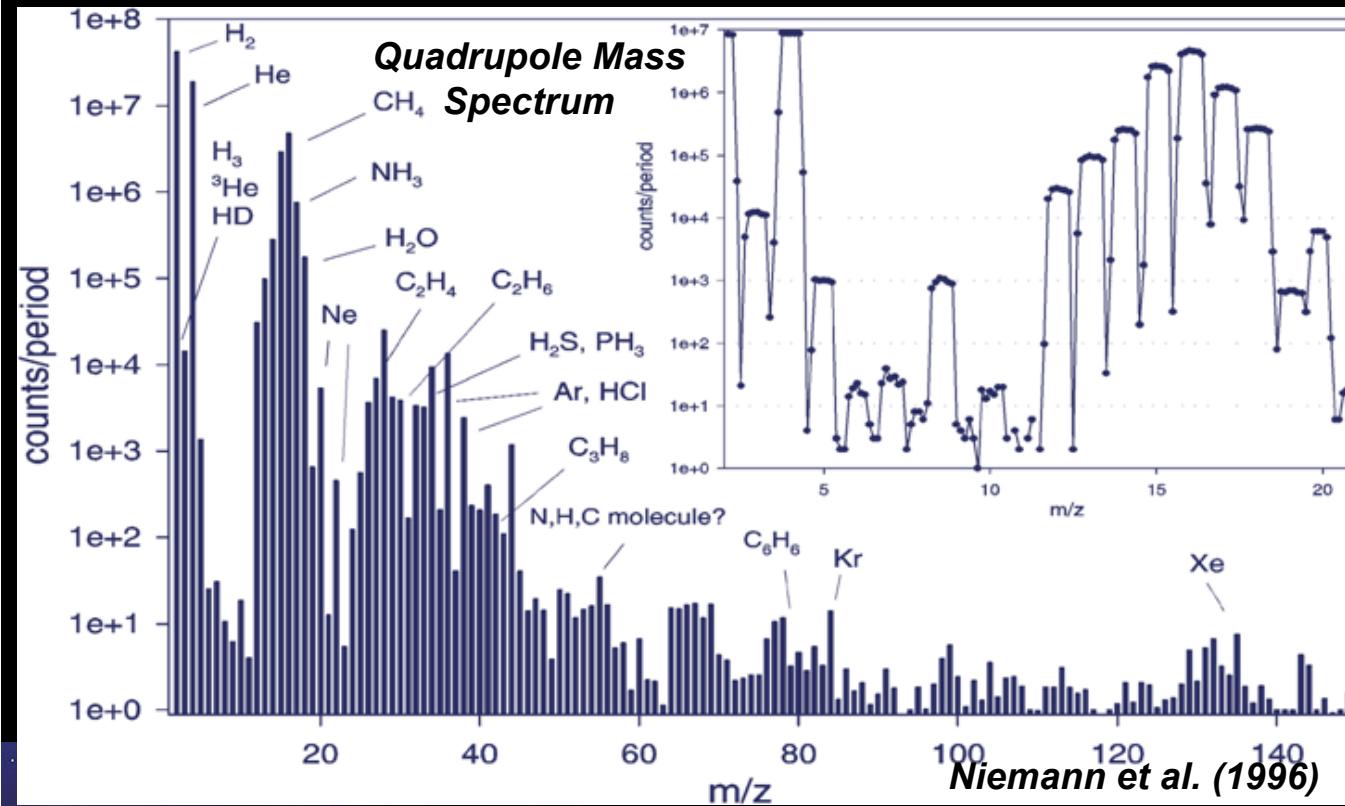
Vacuum Pyrolysis

- Highly efficient way to extract volatiles from regolith
- Lunar regolith must be heated to 1200-1400°C to release oxygen (*E. Cardiff and K. Neff*)
- SAM pyrolysis units designed to heat samples to 1000°C max (*P. Jordan*)



- Thermal models predict ovens will reach 1300°C with 34W heater power (*C. Simmons*)
- VAPoR oven experimental testing underway at Goddard (*T. Stephenson and E. Cardiff*)

Quadrupole Mass Spectrometer Heritage



Comets: CONTOUR
NGIMS (selected for 2011
LADEE Lunar Orbiter)

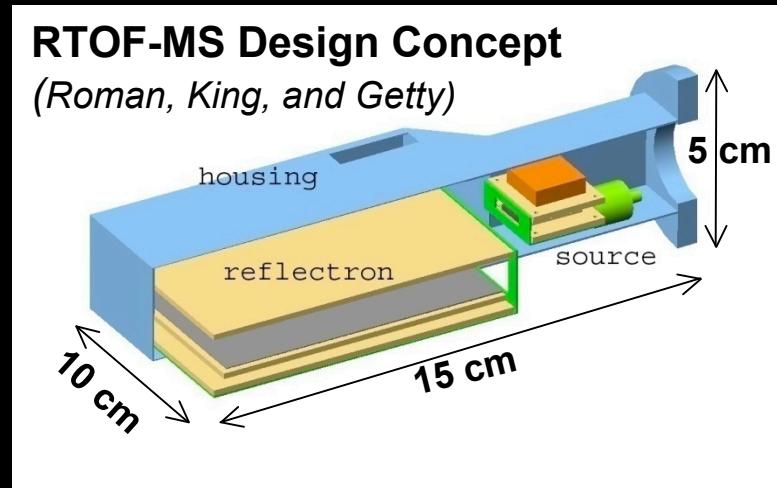


Saturn: Cassini INMS
Titan: Huygens Probe GCMS

ASTID Miniature Time of Flight Mass Spectrometer Development at Goddard

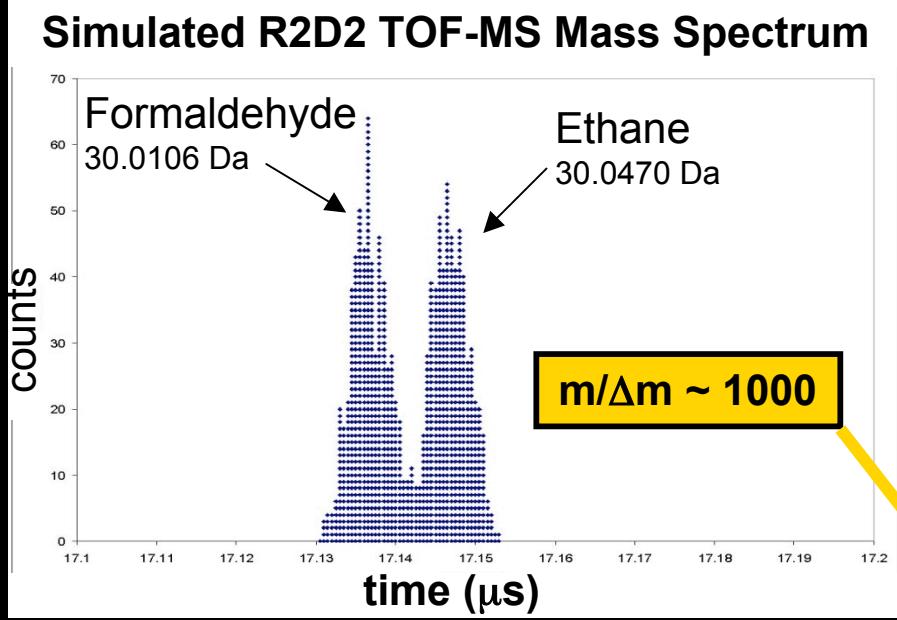
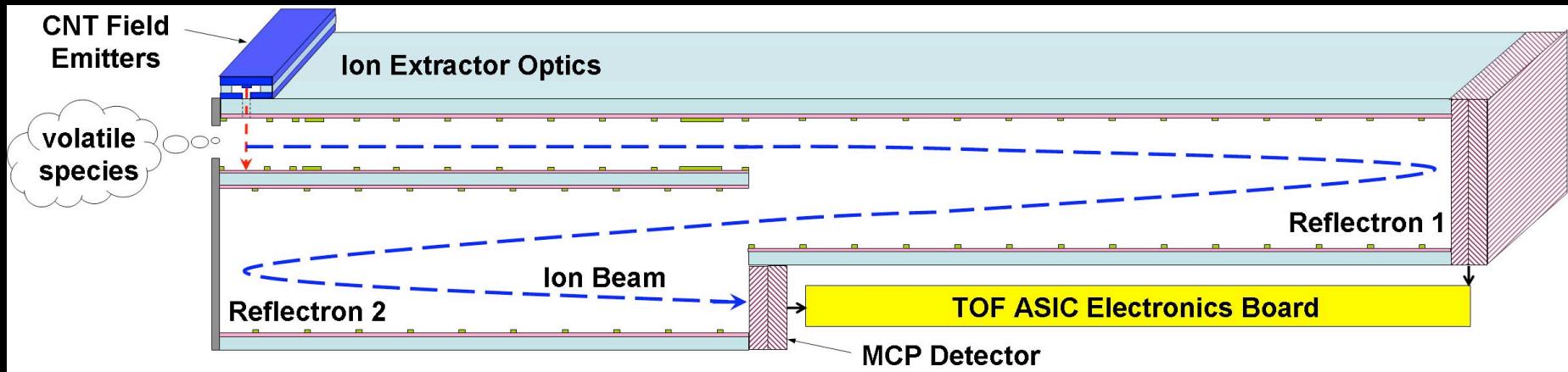
A miniature reflectron time of flight mass spectrometer (RTOF-MS) is one of the candidates for VAPoR. It includes:

- Microfabricated ion optics
- Nanofabricated CNT field emission e-gun



Parameter	SAM QMS	VAPoR TOF-MS
Mass Range	2-535 Da	1-1000 Da
Mass Resolution ($m/\Delta m$)	65-1000	1000
System Mass	3.2 kg	2.2 kg
System Power	27.2 W	6.3 W
Core Volume	3000 cm ³	1130 cm ³
Dynamic Range	10^6 - 10^8	10^6
Sensitivity (cps/N ₂ /cc)	5×10^{-3}	1×10^{-3}

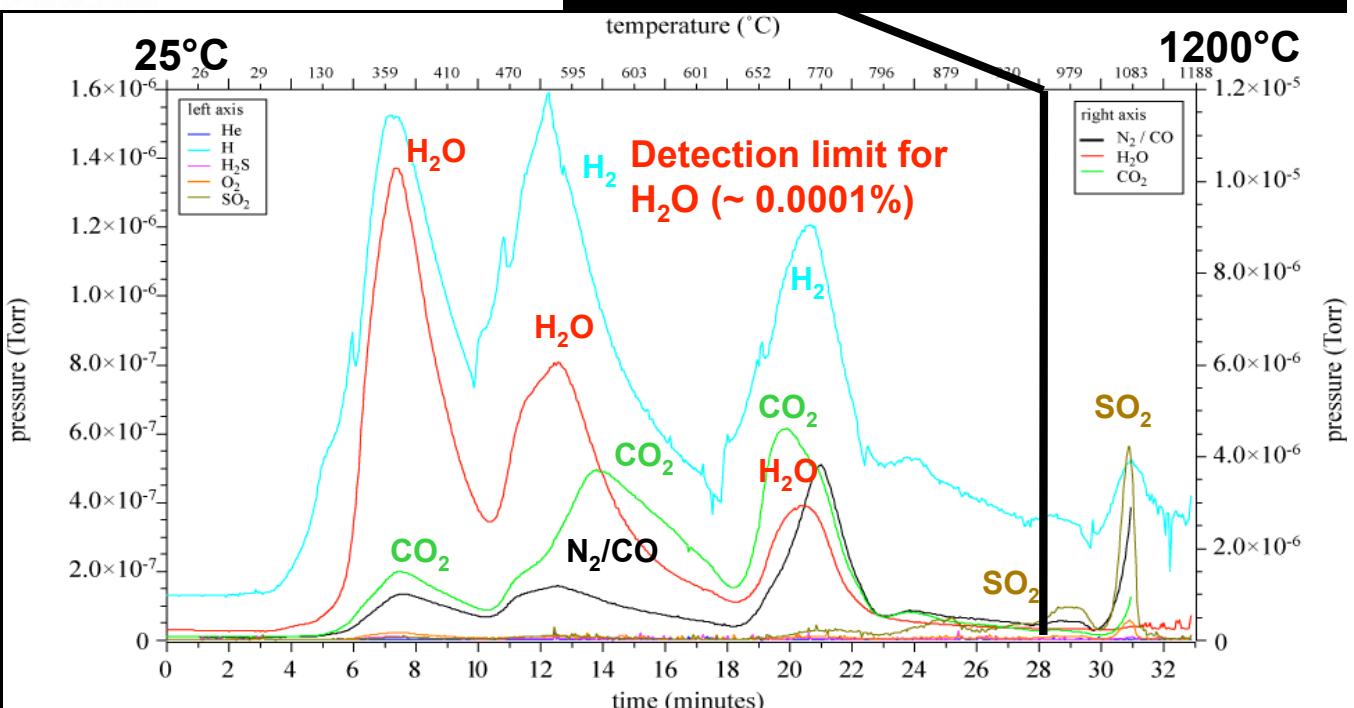
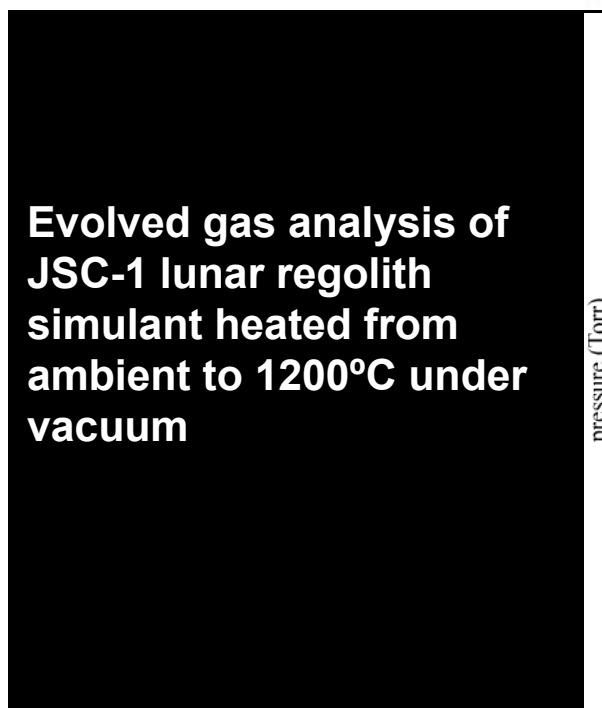
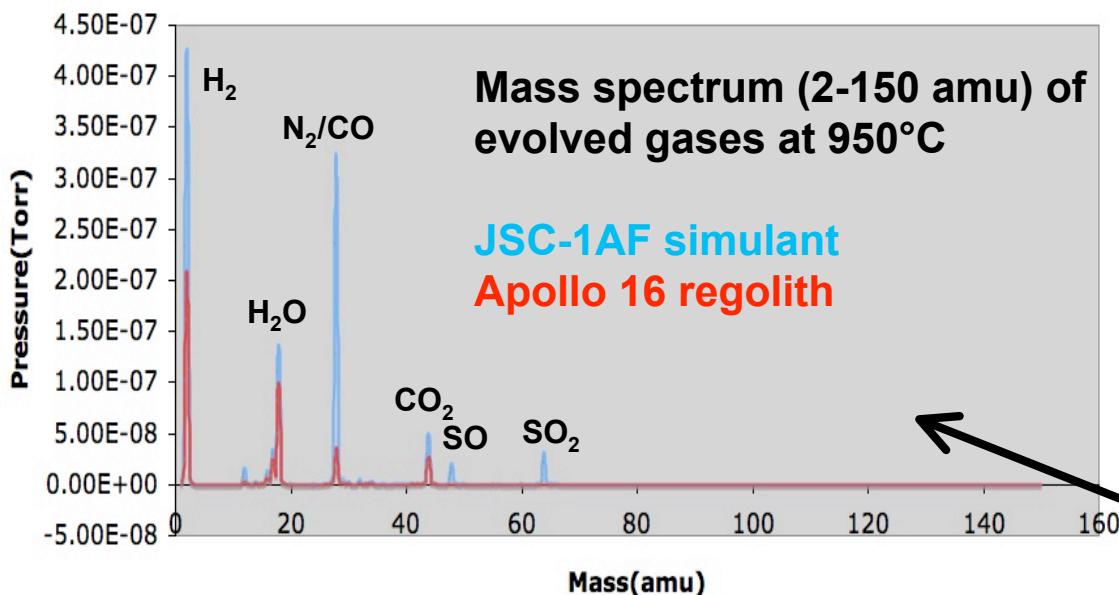
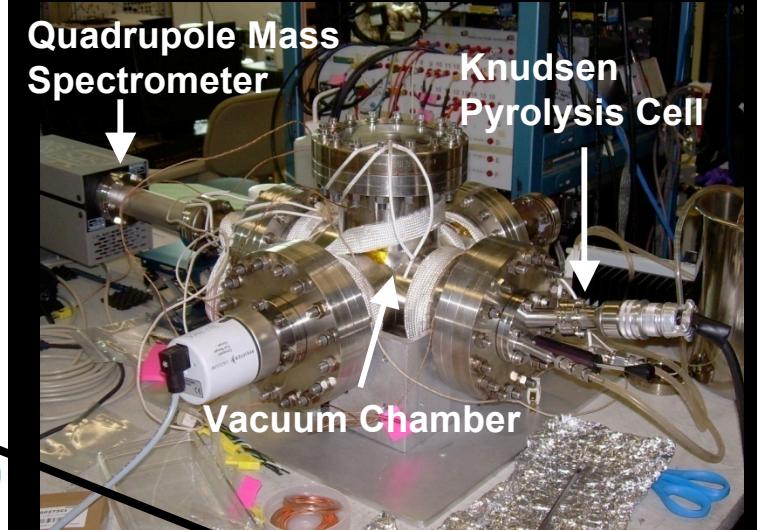
“Double-Reflectron” R2D2 TOF-MS



	Species of Interest	Exact Mass (Da)	Δm (Da)	Resolution ($m/\Delta m$)
RTOF-MS	H ₂ O	18.0106	1.0061	19
	HDO	19.0167		
	¹⁴ N ¹⁴ N	28.0061	0.9971	29
	¹⁴ N ¹⁵ N	29.0032		
	HD	3.0219	0.0059	511
	³ He	3.0160		
R2D2 TOF-MS	N ₂ H ₄	32.0374	0.0476	672
	O ₂	31.9898		
	NDH ₂	18.0328	0.0222	811
	H ₂ O	18.0106		
	C ₂ H ₆	30.0470	0.0364	824
	H ₂ CO	30.0106		

VAPoR Prototype

I. L. ten Kate and C. Malespin (2008)



Future Opportunities

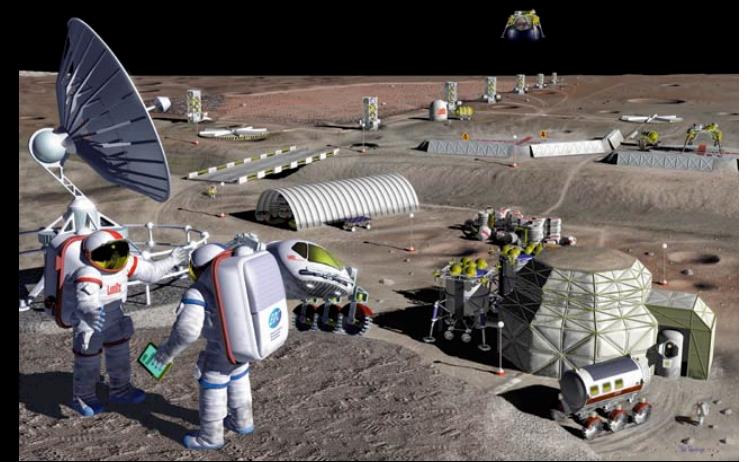


Robotic Exploration

- Crater lander, hopper, rover, tetwalker
- Determine H abundance, composition, and distribution at crater rim and interior
- Measure variability and abundance of water-ice and other volatiles inside crater
- ISRU enabling technology

Human Exploration (>2018)

- Moon as test-bed for in situ volatile analyses to understand human contamination of atmosphere and regolith.
- Ability to identify volatile-rich samples for return to Earth.



Acknowledgments

- NASA Lunar Sortie Science Opportunites (LSSO) and NASA Goddard Internal Research and Development (IRAD) Programs for supporting the VAPoR instrument concept study (2007-2008).
- NASA Astrobiology Science and Technology Instrument Development (ASTID) Program for miniature mass spectrometer and VAPoR prototype development support (2004-2012).